WORK OF BREATHING LIMITS
FOR HELIOX BREATHING

Navy Experimental Diving Unit

Author: D. Warkander, Ph.D.

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING AUTHORITY	

4. PERFORMING ORGANIZATION REPORT NUMBER(S) NEDU Technical Report No. TR 10-14	5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Navy Experimental Diving Unit	6b. OFFICE SYMBOL (If Applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) 321 Bullfinch Road, Panama City, FL 32407-7015		7b. ADDRESS (City, State, and Zip Code)
8a. NAME OF FUNDING SPONSORING ORGANIZATION NAVSEA 00C3	8b. OFFICE SYMBOL (If Applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code) 2531 Jefferson Davis Highway, Arlington, VA 22242-5160	10. SOURCE OF FUNDING NUMBERS			
	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO. TA 10-06	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)   (U)   WORK OF BREATHING LIMITS FOR HELIOX BREATHING

12. PERSONAL AUTHOR(S)   D. Warkander, Ph.D.

13a. TYPE OF REPORT
   Technical Report
	13b. TIME COVERED
	   FROM Oct 2009 TO Sep 2010
		14. DATE OF REPORT (Year, Month, Day)
		2010 November 12
			15. PAGE COUNT
			   29

16. SUPPLEMENTARY NOTATION

17.	COSATI CODES		18. SUBJECT TERMS
FIELD	GROUP	SUB-GROUP	diving, underwater breathing apparatus, exercise limitation, breathing resistance, resistive effort, standard.

19. ABSTRACT: The purpose of the present report was to determine physiologically acceptable limits for work of breathing with heliox mixtures. The basis for the development was the limits for air breathing that Navy Experimental Diving Unit (NEDU) implemented in 2008. Two ways of converting the air limits to heliox were considered: empirical changes in breathing capacity and calculations of equivalent gas density. The reasons for choosing changes in breathing capacity are discussed. Limits are presented for diving with fixed concentrations of oxygen (e.g., open circuit diving) and fixed partial pressure of oxygen (e.g., electronic rebreathers). Tables give limits for common gas mixtures or ways to calculate the limits for custom gas mixtures. The results are compared to those from previous tests at NEDU. No restrictions will be put on existing equipment. Rather, in some situations the limits will increase, a result making the advantages of heliox increasingly obvious.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT [ ] UNCLASSIFIED/UNLIMITED [X] SAME AS RPT. [ ] DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
   NEDU Librarian
	22b. TELEPHONE (Include Area Code)
	   850-230-3170
		22c. OFFICE SYMBOL

DD Form 1473 SECURITY CLASSIFICATION OF THIS PAGE   UNCLASSIFIED

ACKNOWLEDGMENTS

CONTENTS

TABLES

FIGURES

ABBREVIATIONS AND DEFINITIONS

V_T = tidal volume (L), the total volume exhaled in each breath

WOB   = work of breathing (J), the integral of pressure as a function of volume

WOB/V_T = work of breathing/tidal volume, also known as resistive effort or volume-averaged pressure (J/L = kPa)

PHYSICAL DATA

gas	Density at 0°C, ρ (kg · m^{-3})
Air	1.29
He	0.178
O_2	1.429
N_2	1.25

THIS PAGE BLANK

INTRODUCTION

In 2008 Navy Experimental Diving Unit (NEDU) adopted new limits[1] on acceptable work of breathing (WOB) in underwater breathing apparatus (UBAs) used by air-breathing divers:

$$WOB/V_T = 2.99 - 0.021 \cdot depth \text{ (depth in meters of salt water [msw]), and} \quad (1)$$
$$WOB/V_T = 2.99 - 0.00636 \cdot depth \text{ (depth in feet of salt water [fsw]).} \quad (2)$$

WOB/V_T is expressed in kPa (i.e., J/L). At 50 msw (165 fsw), Equation 2 gives a limit of 1.94 kPa.

Based on physiological data from experiments with divers,[2] these limits superseded previous WOB goals[3] that had been based on the performance of commercial UBAs around 1980.

The new limits allow less WOB/V_T as depth increases. As the gas density increases with depth, the work required to move gas from the mouth into the lungs and out again increases. Since the respiratory muscles do not get stronger with depth, the effort available to move gas decreases with depth.

The phenomenon of the limits changing with gas density lends itself to develop new limits for heliox diving, too. Physiologically based WOB limits during heliox diving could be obtained in two ways:

1. Manned dives. Such dives with heliox-breathing subjects would require two to three years of intense diving. The depths involved, 300 fsw (91 msw) and deeper, require very long decompressions, and a much improved set of limits on WOB would not be guaranteed.
2. Recalculation. Based on the known gas densities of air and on empirical data showing how breathing capacity changes with gas density, the known air limits could be used and converted to heliox limits.

Existing goals and limits for heliox
Since 1981, NEDU has had goals[3] for UBAs used with heliox (Table 1). In addition, two European standards for UBAs are used with heliox: open circuit umbilical-supplied apparatus (EN 15333),[4] and self-contained rebreathing apparatus (EN 14143)[5] (Table 2). These goals and limits are illustrated in Figure 1. The limits set in the European standards are based on the performance of UBAs commercially available in the late 1970s — i.e., more than 30 years ago.[6]

Table 1. NEDU resistive effort goals for the different categories of UBAs and different test parameters used to achieve certain RMVs.

Minute ventilation	breathing frequency	tidal volume	Category 1 0 to 198 fsw, air	Category 2 0 to 198 fsw, air; 0 to 1000 fsw, HeO$_2$	Categories 3 and 5 0 to 200 fsw, air; 0 to 1500 fsw, HeO$_2$	Category 4 0 to 150 fsw, air	Category 4 0 to 1500 fsw, HeO$_2$
(L/min)	(breaths per minute)	(L)	(kPa)	(kPa)	(kPa)	(kPa)	(kPa)
22.5	15	1.5	1.37	1.76	0.231	0.170	0.231
40	20	2.0	1.37	1.76	0.617	0.509	0.617
62.5	25	2.5	1.37	1.76	1.542	1.172	1.542
75	30	2.5	–	–	2.159	1.696	2.159
90	30	30	–	–	3.085	2.529	3.085

TM 01-94[3] uses these definitions: Category 1. Open Circuit Demand UBA; Category 2. Open Circuit Umbilical-Supplied Demand UBA; Category 3. Open Circuit Umbilical-Supplied Free Flow UBA; Category 4. Closed- and Semiclosed Circuits, Breath-Powered UBA; and Category 5. Semiclosed Circuit, Ejector or Pump-Driven UBA.

Table 2. Limits for WOB/V_T presented by two European standards.

standard	Minute ventilation (L/min)	WOB/V_T (kPa)
EN15333[1]	62.5	2.375
EN15333[2]	75	3.5
EN14143[3]	75	2.75

[1]sections 5.7.1.1 and 6.5.2
[2]sections 5.7.1.2 and 6.5.2
[3]sections 5.6.1.1 and 5.6.1.2
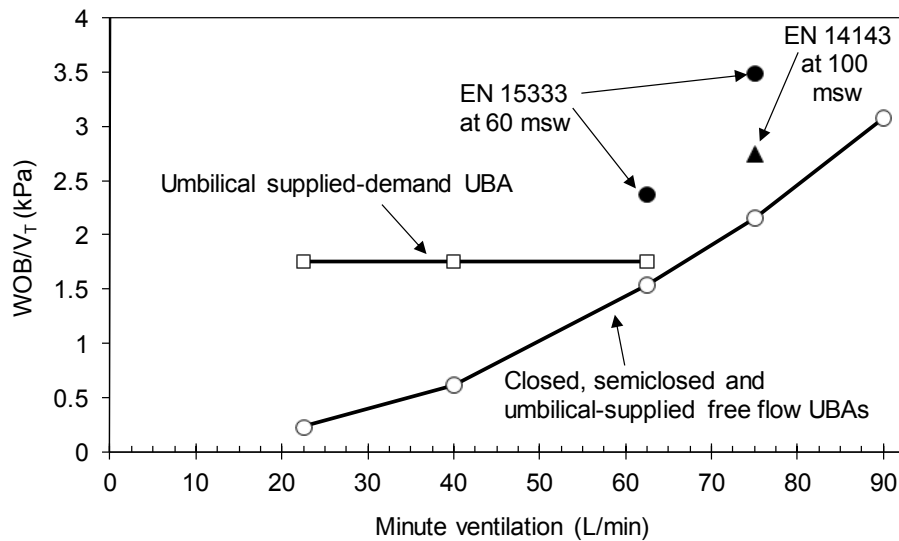
Figure 1. NEDU's existing limits for heliox breathing and two European limits.

Purpose of the present report
The purpose of the present report was

1. to determine acceptable limits for WOB with heliox based on existing physiologically based air limits,
2. to compare these new limits to existing goals and limits, and
3. to compare the performance of existing UBAs to the new limits, so that the consequences of adopting such limits can be known.

Limits will be developed for two general types of UBA. Some UBAs provide a fixed concentration of O_2 (FO_2; i.e., open circuit), while others (e.g., rebreathers) provide a constant partial pressure of O_2 (PO_2). The limits will be calculated separately for these two types.

THIS PAGE BLANK

METHODS

Two approaches for converting the known limits for air breathing to heliox breathing were considered:

1. empirical changes in breathing capacity, and
2. calculating equivalent gas density.

Each approach will be discussed separately.

Empirical changes in breathing capacity

Changes in breathing capacity have been studied extensively as a limitation to breathing at depth. Lanphier and Camporesi[7] write that —One of the most prominent factors is the restriction of ventilatory capacity by the increased density of gas at depth."

The scientific literature indicates that divers' breathing capacity changes with the relative gas density (RGD) as RGD^k. RGD is calculated as the ratio between two gas densities at the same pressure and temperature. Table 3 compiles the empirical values found. Similarly, Table 4 compiles values for k for expiratory flows.

Table 3. Empirical values of the exponent k for maximum breathing capacity as given by various authors.

Authors	Value
Wood, Leve and Workman[8]	0.48^a
Marshall, Lanphier and DuBois[9]	0.50
Anthonisen et al.[10]	0.39
Anthonisen[10] (inspiratory only)	0.47

[a] as calculated by Wood and Bryan[11]

Table 4. Empirical values of the exponent k for expiratory flow given by various authors.

Authors	Value
Wood, Bryan;[11] peak flow	0.41
Wood, Bryan,[11] at 75 to 25% vital capacity	0.43–0.46
Wood, Leve and Workman[8]	0.45^a
Anthonisen et al,[10] at 50% vital capacity	0.46
Anthonisen et al;[10] peak flow	0.44

[a] as calculated by Wood and Bryan[11]

The maximum WOB/V_T that can consistently be sustained from respiratory muscles has empirically been determined to be 4.29 kPa.[2] This value, in combination with eq. 1, shows that the maximum WOB/V_T to overcome the internal work of breathing with air at 1 atmosphere absolute (ata) is 4.29 – 2.99 = 1.30 kPa.

The switch to a gas with lower density changes the limit on WOB/V_T in two ways:

1. The starting value (offset) increases and approaches the 4.29 kPa limit.
2. The slope of the line decreases.

$$\text{Limit} = W_{max} - W_{int} \cdot RGD^k - \text{slope} \cdot \text{depth} \cdot RGD^k , \qquad (3)$$

where W_{max} is the maximum WOB/V_T and W_{int} is the internal WOB/V_T. Equation (1) states that Wmax is 4.29 kPa, W_{int} is 1.30 kPa and slope is 0.021 kPa/msw.

Equation (3) can be simplified to the form

$$\text{Limit} = A - B \cdot \text{depth}, \qquad (4)$$

where $A = W_{max} - W_{int} \cdot RGD^k$ and $B = \text{slope} \cdot RGD^k$.

The empirical values for k are consistently in the range 0.39 to 0.50. For the safest limits on acceptable WOB/V_T, k = 0.4 is chosen. The difference from 0.5 to 0.4 is about 5–7%.

Example 1. Switching from air to heliox (79/21):

ρ_{air} = 1.29 kg $\cdot$ m^{-3},
$\rho_{heliox\ (79/21)}$ = 0.79 $\cdot$ 0.178 + 0.21 $\cdot$ 1.429 = 0.14 + 0.30 = 0.44 kg $\cdot$ m^{-3}
RGD^k = $(0.44/1.29)^{0.4}$ = $0.341^{0.4}$ = 0.65

Thus,

A = 4.29 – 1.30 $\cdot$ 0.65 = 3.44 kPa and
B = 0.021 $\cdot$ 0.65 = 0.0136 kPa/msw.

The limit for heliox (79/21) becomes

$$\text{Limit} = 3.44 - 0.0137 \cdot \text{depth (in msw)}. \qquad (5)$$

Example 2. Similar calculations for heliox (88/12) make the limit

$$\text{Limit} = 3.54 - 0.0122 \cdot \text{depth (in msw)}. \qquad (6)$$

The limits for these two heliox mixtures are illustrated in Figure 2. For comparison, the limits for air are also included. Note the large increase in limits when a switch to heliox is being made — and the relatively small change between the two heliox mixtures.
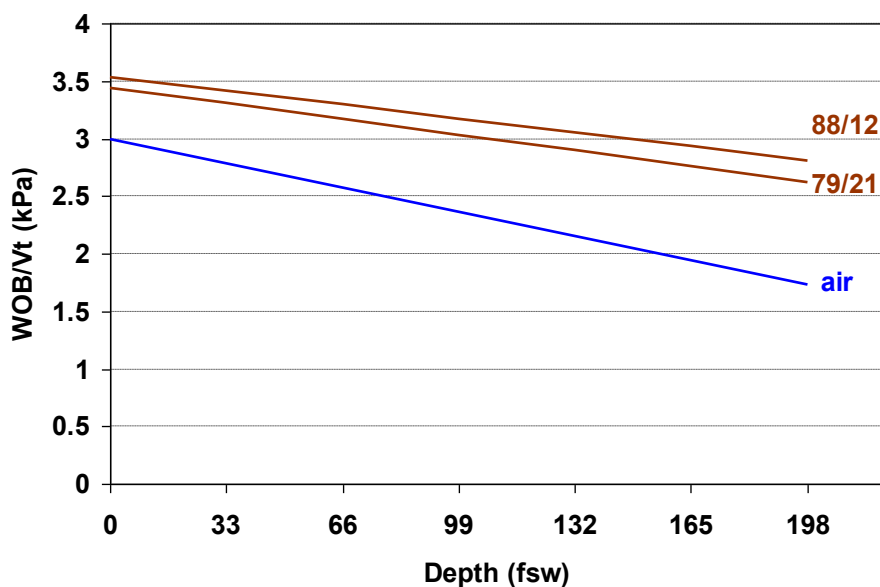
Figure 2. Work of breathing limits for air and two heliox mixtures.

With increasing depths, the FO_2 has to decrease in order to limit the PO_2. Therefore, calculations of limits for depths beyond depths in Figure 2 have been extended to heliox (98/2) and heliox (99/1) and are illustrated in Figure 3. Table 5 presents values for the coefficients A and B for the heliox mixtures where the FO_2 varies in the range 1 through 21%.
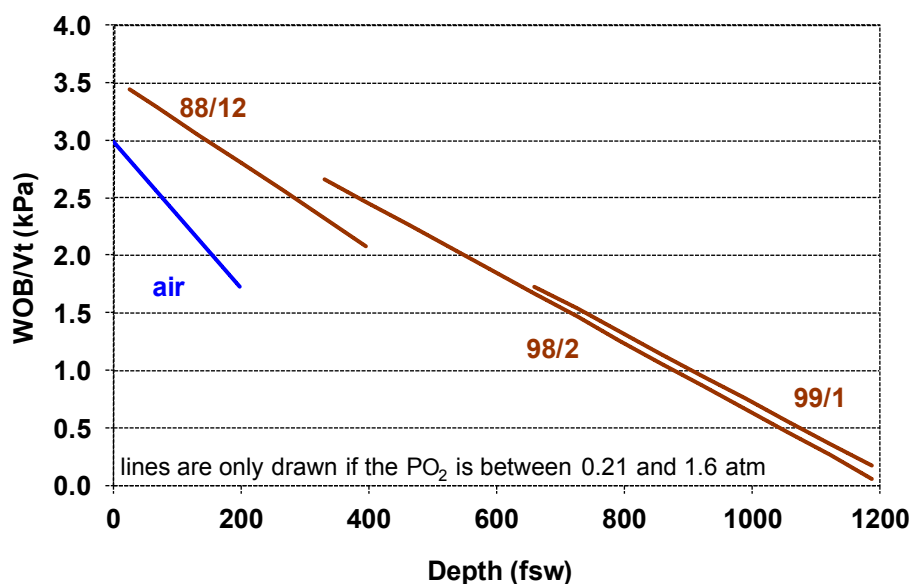
Figure 3. WOB limits for air and two heliox mixtures.

Table 5. Coefficients for use in equation (4) to determine the acceptable WOB/V_T for heliox mixtures with different concentrations of O_2.

FO_2 (%)	A (kPa)	B (kPa/msw)	B (kPa/fsw)
21	3.44	0.0137	0.00414
20	3.45	0.0135	0.00410
19	3.46	0.0134	0.00405
18	3.47	0.0132	0.00400
17	3.48	0.0130	0.00395
16	3.49	0.0129	0.00390
15	3.50	0.0127	0.00385
14	3.52	0.0125	0.00379
13	3.53	0.0123	0.00374
12	3.54	0.0122	0.00368
11	3.55	0.0120	0.00363
10	3.56	0.0118	0.00357
9	3.57	0.0116	0.00351
8	3.59	0.0114	0.00345
7	3.60	0.0112	0.00338
6	3.61	0.0110	0.00332
5	3.63	0.0107	0.00325
4	3.64	0.0105	0.00318
3	3.65	0.0103	0.00311
2	3.67	0.0100	0.00304
1	3.68	0.0098	0.00296

Calculations for fixed P_{O_2}

The calculations for UBAs with fixed P_{O_2} are made by determining what the FO_2 would be for a given P_{O_2} at a given depth. The calculated FO_2 is then used to determine the limit. Results from these calculations are shown in Figure 4 and Table 6.
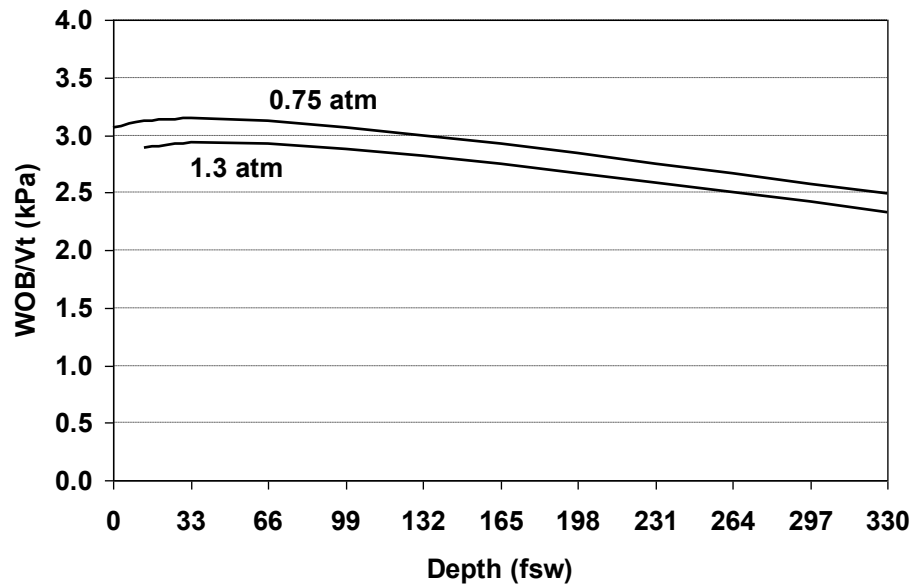
Figure 4. WOB limits for two heliox mixtures with constant P_{O_2}.

Table 6. Limits on WOB/V_T for heliox mixtures with fixed P_{O_2} of either 0.75 or 1.3 atm.

Depth		P_{O_2}	
fsw	msw	0.75	1.3
0	0	3.06	-
16	5	3.13	2.90
33	10	3.14	2.93
66	20	3.12	2.93
99	30	3.07	2.88
132	40	3.00	2.82
165	50	2.92	2.75
198	60	2.84	2.67
231	70	2.75	2.59
264	80	2.67	2.50
297	90	2.58	2.42
330	100	2.49	2.33

Comparisons to existing goals and limits for heliox
The current NEDU goals[3] for all heliox breathing and two European standards[4, 5] are illustrated in Figure 5. The new limits for two depths when heliox 88/12 is being breathed are also shown.

8
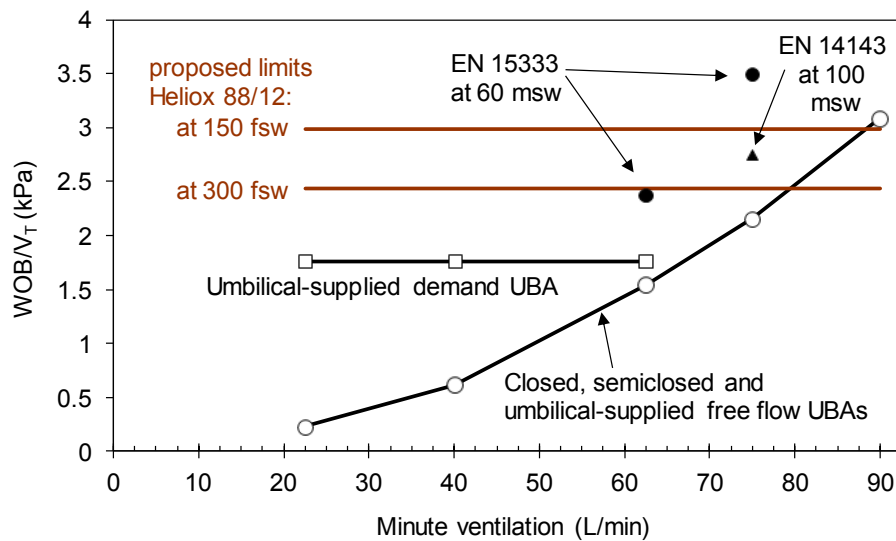
Figure 5. Existing goals[3–5] and two proposed limits for WOB/V_T for heliox breathing. Also shown are two limits for heliox 88/12, one for 150 fsw and one for 300 fsw.

Calculations of equivalent gas density

For a given heliox mixture and depth, the gas density can be calculated. The depth at which air has the same gas density can then be calculated, and the WOB/V_T limit can be determined.

Example A. Heliox 79/21 has a density of 3.08 kg/m^3 at 60 msw (198 fsw). This is the density of air at 14 msw (46 fsw). From the air limits given by Equation 1, the acceptable WOB/V_T at this depth would be 2.70 kPa. Similarly, heliox 79/21 at 19.2 msw (63 fsw) has the same density as air at the surface, a fact which means that the acceptable WOB/V_T at this depth would be 2.99 kPa.

Example B. Heliox 88/12 has a density of 2.30 kg/m^3 at 60 msw (198 fsw) — i.e., the density of air at 7.8 msw (26 fsw). The acceptable WOB/V_T for heliox 88/12 at 60 msw would be 2.83 kPa. Similarly, heliox 88/12 at 29 msw (96 fsw) has the same density as air at the surface, where the acceptable WOB/V_T is 2.99 kPa.

Example C. For use in really deep diving, heliox 99/1 has a density of 5.91 kg/m^3 at 300 msw (990 fsw) — i.e., that of air at 35.9 msw (118 fsw). The acceptable WOB/V_T at 300 msw would be 2.24 kPa. Similarly, heliox 99/1 at 58 msw (190 fsw) has the same density (but insufficient PO_2) as air at the surface, where the acceptable WOB/V_T is 2.99 kPa.

Example D. At a depth of 450 msw (1485 fsw), heliox 99/1 has a density of 8.76 kg/m^3 — i.e., that of air at 58 msw (190 fsw). The acceptable WOB/V_T would be 1.77 kPa.

9

Example E. At the extreme depth of 700 msw, heliox 99/1 has a density of 13.5 kg/m^3 — i.e. that of air at 95 msw (314 fsw). The acceptable WOB/V_T would be 0.99 kPa.

Example F. It is first at 1020 msw (3370 fsw) that the acceptable WOB/V_T with heliox 99/1 has decreased to zero.

DISCUSSION

Selection of conversion method

The two methods considered for converting from air limits to heliox limits give similar numbers for shallow to moderate diving depths. For instance, Figure 2 shows a limit of 2.81 kPa at 60 msw (198 fsw), while Example B calculates a limit of 2.83 kPa. However, at greater depths the two methods start to differ. At 300 msw (990 fsw), Figure 3 indicates a limit of 0.75 kPa for heliox 99/1, while Example C calculates a limit of 2.24 kPa — three times greater. As the density equivalence method seems to indicate via Example F, it would be possible for most people to dive to depths greater than 1,000 msw (3300 fsw). Since this is in fact not possible, however, the density equivalence method will not be used.

Use of the method based on empirical changes in breathing capacity

Figure 3 indicates that it would not be possible to dive much deeper than some 1200 fsw (360 msw), even though it is well known that it is possible to do so. Such a prediction is a reflection on limits in general, because limits must be set so that loads are tolerated by most people. In the case of deep diving, it is also known that such diving is not for everybody, a fact indicating that divers choose to pursue deep diving by self-selection — or that they have either unusual abilities or specialized training.

The goal for rebreathers shown in Figure 1 and Table 2 has been difficult to meet at low minute ventilations. As stated elsewhere,[3] even at the surface (with N_2O_2) the MK 16 does not meet the goal at low minute ventilations. The new limits avoid this apparent problem.

Figure 4 has what may seem like odd-looking curves. The acceptable work of breathing at first increases as depth increases, because O_2 has a greater density than air. At great depths the lines are fairly straight, similar in nature to the fixed FO_2 limits. However, close to the surface the O_2 concentration changes rapidly — a change that gives the limit lines their curved patterns.

Comparisons to existing goals and limits for heliox

<u>NEDU goals</u>

<u>Open circuit demand UBA</u>
Numerically, the new limit with Heliox 88/12 at 300 fsw and 62.5 L/min is about 40%
greater (2.44 vs. 1.76) than the current limit for umbilical-supplied diving (Figure 5).

<u>Rebreather UBA</u>
The proposed new limits for rebreather diving are higher than the existing NEDU limits,[3]
at least at minute ventilations of ≤ 75 L/min. For the minute ventilation at which
decisions are made (62.5 L/min), the new limit is 56% greater (2.41 vs. 1.542).

However, it must be borne in mind that the statistical analysis will verify whether a
measured average is *below* a given limit, rather than whether such a measured
average *does not exceed* it."[2]

<u>Example 1</u>. For an umbilical-supplied UBA the goal was 1.76 kPa and the previously
NEDU-allowed standard deviation was 0.2 kPa.[2] Assume a sample of five UBAs. If a
confidence interval is calculated, the greatest value that the mean WOB/V_T could have
is 1.76 + 0.2 · 2.776[‡] / √5 = 1.76 + 0.25 = 2.01 kPa. With typical statistical analysis, the
sample mean must be below a limit. Thus, the maximum sample mean would be 2.44 –
0.25 = 2.19 kPa. Therefore, with typical statistical analysis the new limit is about 9%
greater (2.19 vs. 2.01).

<u>Example 2</u>. For a rebreather UBA the goal at 62.5 L/min was 1.542 kPa and the
previously allowed NEDU standard deviation was 0.2 kPa.[2] Assume a sample of five
UBAs. The upper bound of the confidence interval is 1.542 + 0.25 = 1.79 kPa. The
maximum sample mean would be 2.41 – 0.25 = 2.16 kPa. Therefore, with typical
statistical analysis the new limit is about 21% greater (2.16 vs. 1.79).

Reflecting the advantages of heliox breathing, the new limits will allow somewhat
greater WOB/V_T with Heliox.

<u>European standards</u>

<u>Open circuit demand UBA</u>
For a minute ventilation of 62.5 L/min, the EN 15333 limit is 2.375 kPa (Table 1) at 60
msw (198 fsw) with any heliox mixture. A gas that has the highest permissible PO_2 of
1.6 bar[5] at a pressure of 7 bar (60 msw) would be a worst case and would have an O_2
concentration of 23%. The new limit at this depth with a heliox 77/23 blend would be
2.58 kPa. Thus, the EN 15333 could be allowed to be about 9% greater than before.

For a minute ventilation of 75 L/min, the EN 15333 limit is 3.5 kPa (Table 1) at 60 msw
(198 fsw) with any heliox mixture. At this depth the new limit with heliox 77/23 would be

---

[‡] The Student's t-distribution with four degrees of freedom and area of 0.95 gives a value of 2.776.

2.58 kPa. Thus, the EN 15333 limit is far too high, and the UBA will either restrict the diver or create an unsafe situation.

<u>Rebreather UBA</u>
The EN14143 limit is 2.75 kPa. The new limits for 100 msw and a P_{O_2} of 1.3 is 2.33 kPa. Thus, the EN14143 is excessive by about 18%.

Comparisons to previous UBA testing
To determine the consequences of any changes, new limits must be compared to existing test results from several UBAs.

NEDU's normal procedure is to test at least five units of each UBA. But most tests discussed in the following two subsections covering open and closed-circuit breathing apparatus have not included five or more units. Therefore, comparisons serve only to indicate trends and cannot be used to justify any changes to any Navy approval. Such changes are beyond the scope of this report.

Open circuit breathing apparatus

Umbilical-supplied DSI EXO-26 full face mask
Data were extracted from Appendix B of NEDU report TR 03-98[12] and are shown in
Table 7 and plotted in Figure 6. Three masks were tested with heliox (84/16) delivered
through a 600-foot (180 m) umbilical with an internal diameter of 3/8" (9.5 mm) at a
pressure of 165 psi above bottom. The water temperature was 37 °F (3 °C).

Table 7. Work of breathing data from three EXO-26s.

Minute ventilation (L/min)	Depth (fsw)									
	0	33	66	99	132	165	198	231	264	300
22.5	0.82	0.90	1.02	1.08	1.09	1.24	1.25	1.30	1.33	1.22
40	0.95	1.06	1.14	1.21	1.20	1.24	1.25	1.23	1.23	1.38
62.5	1.04	1.13	1.19	1.27	1.29	1.34	1.33	1.30	1.41	1.52
75	1.07	1.15	1.17	1.29	1.39	1.37	1.40	1.44	1.50	1.63
90	1.12	1.21	1.25	1.29	1.40	1.43	1.45	1.54	1.70	2.02
Limit (84/16)	3.49	3.37	3.24	3.11	2.98	2.85	2.72	2.59	2.46	2.34
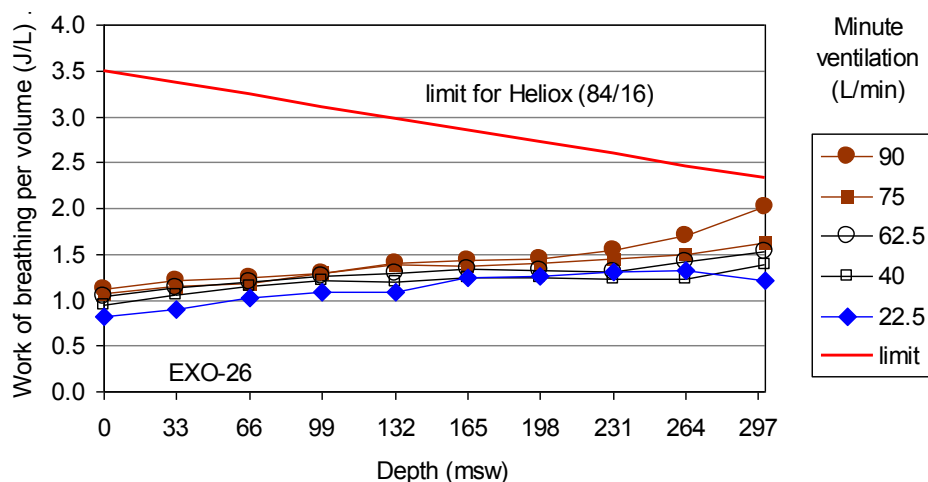
Figure 6. Work of breathing data from three umbilical-supplied EXO-26s with
heliox (84/16).

<u>Kirby Morgan 37</u>
Data were extracted from Table 4 of NEDU report TR 07-05[13] and are shown in Table 8 and plotted in Figure 7. Five KM 37s were tested with heliox 88/12. The report recommends that the KM 37 be approved to a depth of 380 fsw.

Table 8. Work of breathing data from five KM 37s. Breathing gas was heliox (88/12). —"X" means that the pressures recorded were too high for the system to measure.

Minute ventilation (L/min)	Depth (fsw)							
	165	198	231	264	297	330	363	380
22.5	0.97	0.98	0.99	1.03	1.06	1.08	1.07	1.08
40	1.22	1.23	1.28	1.32	1.37	1.38	1.39	1.41
62.5	1.44	1.48	1.57	1.62	1.71	1.75	1.80	1.84
75	1.54	1.59	1.68	1.80	1.93	2.00	2.08	2.18
90	1.69	1.77	1.89	2.04	2.33	2.85	3.29	XP
Limit (88/12)	2.85	2.72	2.59	2.46	2.34	2.21	2.08	2.01
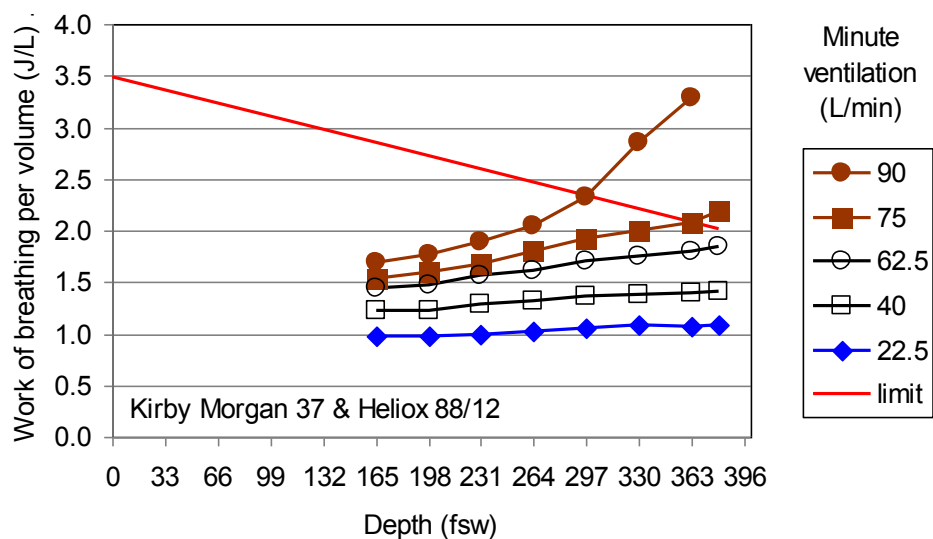
Figure 7. Work of breathing data from five KM 37s with heliox.

Closed-circuit breathing apparatus

Cis-Lunar rebreather
Data were extracted from Table 6 in NEDU report TR 03-02[14] and are shown in Table 9 and plotted in Figure 8. Two rebreathers were tested with a P_{O_2} of 1.3 atm and Sofnolime 812 CO_2 absorbent.

Table 9. Work of breathing data from two Cis-Lunars with heliox.

Minute ventilation (L/min)	Depth (fsw)				
	165	198	231	264	300
22.5	0.82	0.83	0.86	0.85	0.86
40	1.22	1.29	1.32	1.34	1.37
62.5	1.80	1.88	1.98	2.07	2.17
75	2.16	2.27	2.41	2.51	2.66
90	2.62	2.79	2.97	3.15	3.30
Limit (1.3)	2.75	2.67	2.59	2.50	2.41
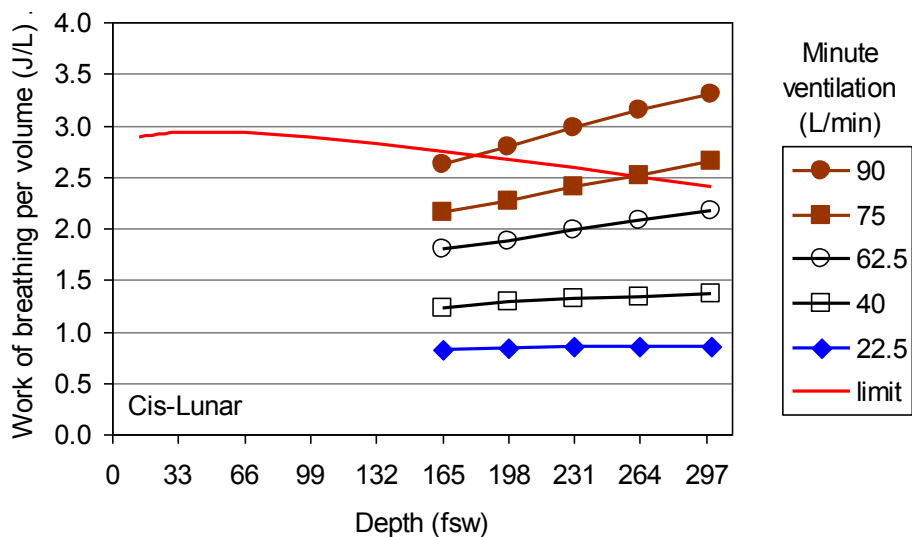
Figure 8. Work of breathing data from two Cis-Lunars with heliox.

AP Diving Inspiration rebreather

Data were extracted from Table 4 in NEDU report TR 03-02[15] and shown in Table 10 and plotted in Figure 9. Two rebreathers were tested with a PO_2 of 1.3 atm and Sofnolime 812 CO_2 absorbent.

Table 10. Work of breathing data from two AP Diving Inspirations.

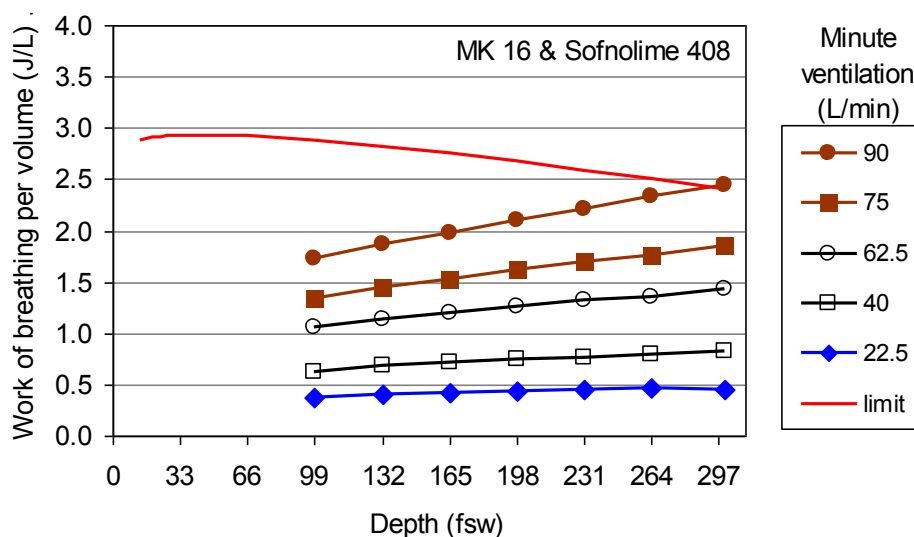| Minute ventilation (L/min)	Depth (fsw)				
	165	198	231	264	300
22.5	0.68	0.67	0.69	0.73	0.75
40	1.17	1.19	1.22	1.28	1.33
62.5	1.97	2.02	2.13	2.24	2.34
75	2.51	2.56	2.69	2.86	2.98
90	3.30	3.41	3.54	3.71	3.92
Limit (1.3)	2.75	2.67	2.59	2.50	2.41
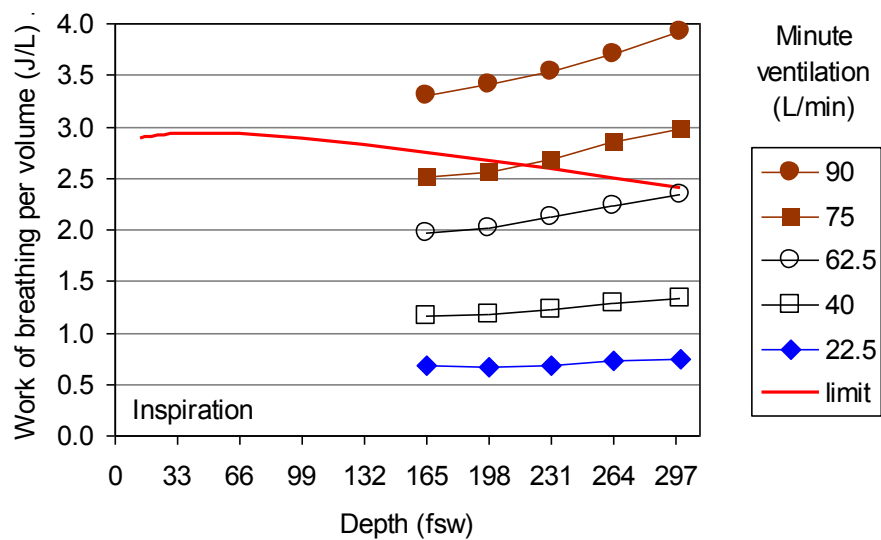
Figure 9. Work of breathing data from two AP Diving Inspirations with heliox.

Data were extracted from NEDU report TR 11-2006.[15] Five MK 16 MOD 2 rebreathers were tested with a PO_2 of 1.3 atm. Tests were made with two types of CO_2 absorbents. Data from tests with Sofnolime 408 are shown in Table 11 and plotted in Figure 10, while data from tests with Sofnolime 812 are shown in Table 12 and Figure 11. Five MK 16s were tested.

Table 11. Work of breathing data from five MK 16 MOD 2s with Sofnolime 408.

Minute ventilation (L/min)	Depth (fsw)						
	99	132	165	198	231	264	300
22.5	0.38	0.40	0.42	0.44	0.45	0.46	0.45
40	0.63	0.68	0.71	0.75	0.77	0.79	0.82
62.5	1.06	1.14	1.20	1.26	1.32	1.36	1.43
75	1.34	1.45	1.53	1.62	1.69	1.76	1.85
90	1.73	1.86	1.98	2.10	2.21	2.33	2.45
Limit (1.3)	2.88	2.82	2.75	2.67	2.59	2.50	2.41

Figure 10. Work of breathing data from five MK 16 MOD 2s with heliox and Sofnolime 408. The limit line drawn is for a PO_2 of 1.3 atm.

Table 12. Work of breathing data from five MK 16 MOD 2s with Sofnolime 812.

| Minute ventilation (L/min)	Depth (fsw)						
	99	132	165	198	231	264	300
22.5	0.42	0.42	0.43	0.44	0.45	0.47	0.48
40	0.65	0.69	0.72	0.76	0.79	0.82	0.85
62.5	1.08	1.18	1.26	1.34	1.41	1.48	1.56
75	1.40	1.53	1.64	1.75	1.86	1.97	2.08
90	1.85	2.01	2.16	2.31	2.45	2.60	2.74
Limit (1.3)	2.88	2.82	2.75	2.67	2.59	2.50	2.41
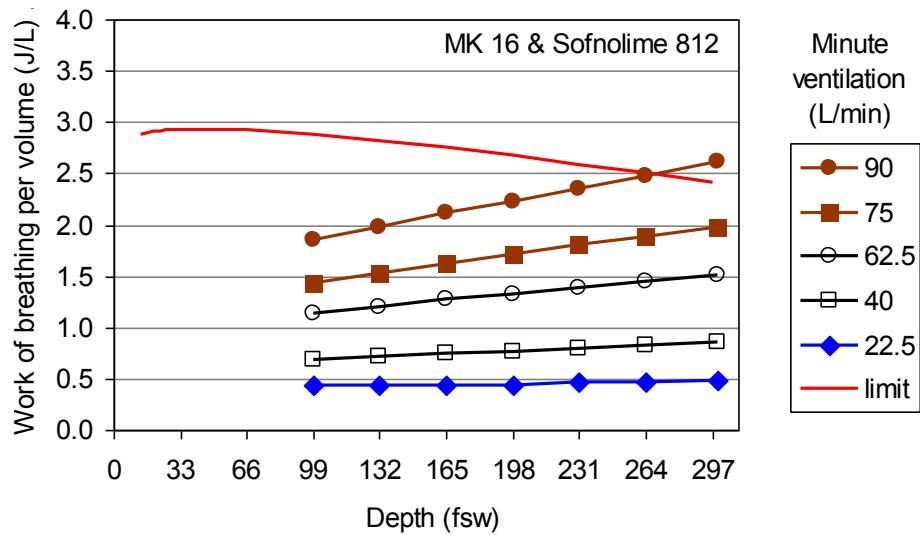
Figure 11. Work of breathing data from five MK 16 MOD 2s with heliox and Sofnolime 812. The limit line drawn is for a P_{O_2} of 1.3 atm.

Stealth EOD-M

Data were extracted from Table 5 in NEDU report TR 05-17[16] and are shown in Table 13 and plotted in Figure 12. Two Stealth EOD-Ms were tested with Sofnolime 812.

Table 13. Work of breathing data from two Stealth EOD-Ms.

| Minute ventilation (L/min)	Depth (fsw)						
	99	132	165	198	231	264	300
22.5	0.62	0.64	0.63	0.64	0.64	0.65	0.65
40	0.84	0.85	0.88	0.88	0.89	0.91	0.93
62.5	1.16	1.20	1.24	1.28	1.31	1.35	1.39
75	1.37	1.43	1.48	1.53	1.59	1.66	1.71
90	1.68	1.75	1.84	1.92	2.00	2.08	2.17
limit (1.3)	2.88	2.82	2.75	2.67	2.59	2.50	2.41
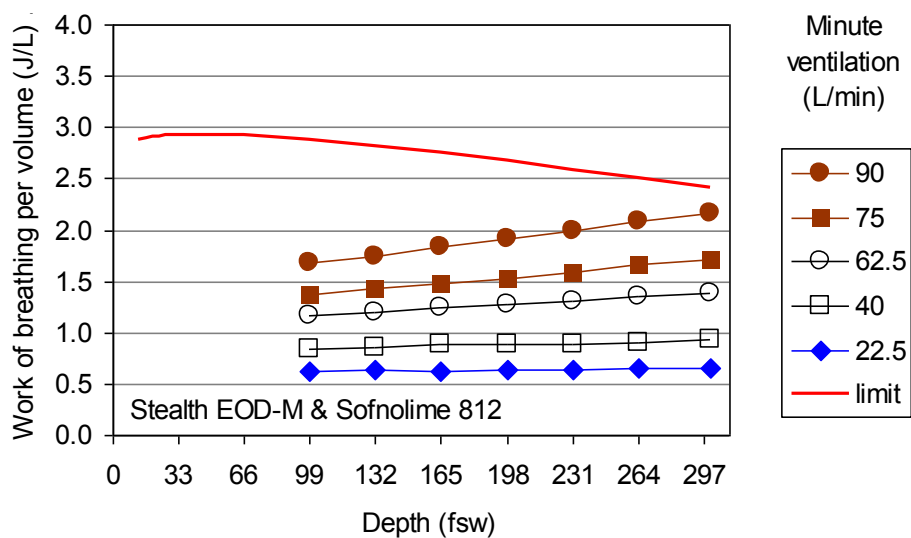
Figure 12. Work of breathing data from two Stealth EOD-Ms with heliox.

19

Viper E

Data were extracted from Table 34 in NEDU report TR 05-17[16] and are shown in Table 14 and plotted in Figure 13. Two Viper Es were tested with Sofnolime 812 CO_2 absorbent.

Table 14. Work of breathing data from two Viper Es.

Minute ventilation (L/min)	Depth (fsw)						
	99	132	165	198	231	264	300
22.5	0.43	0.49	0.51	0.51	0.53	0.53	0.55
40	0.67	0.72	0.75	0.79	0.81	0.82	0.87
62.5	1.03	1.08	1.22	1.28	1.31	1.34	1.45
75	1.25	1.36	1.44	1.55	1.63	1.69	1.82
90	1.59	1.75	1.88	2.00	2.13	2.19	2.37
limit (1.3)	2.88	2.82	2.75	2.67	2.59	2.50	2.41
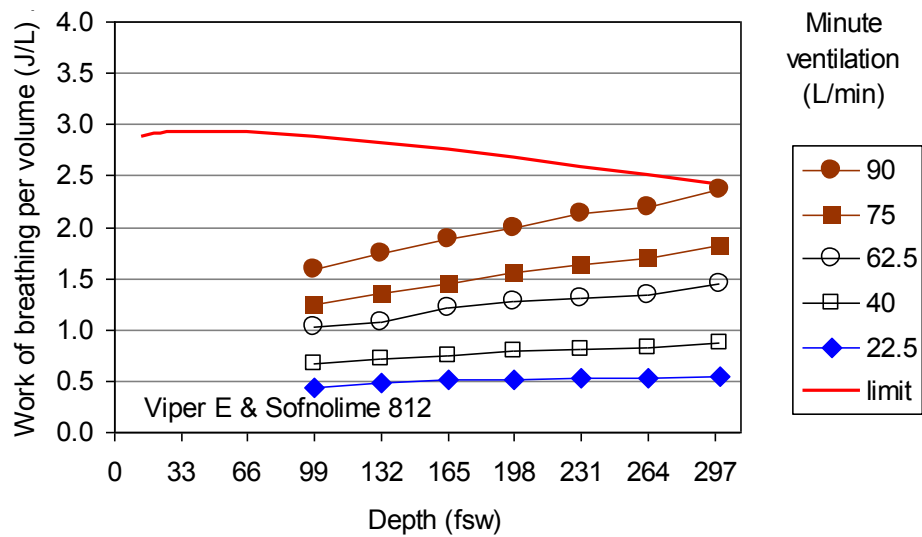
Figure 13. Work of breathing data from two Viper Es with heliox.

THIS PAGE BLANK

CONCLUSIONS

New limits on WOB imposed by diver UBAs have been developed for use with heliox. These limits, which vary with heliox mixture and depth, have been derived from air limits that were developed from studies of divers' physiological responses to breathing resistance. Thus, the derivation of these limits differs widely from that of the existing limits and goals, which were based on the performance of breathing apparatus commercially available some 30 years ago. Adopting the new limits will not impose any restrictions on existing UBAs but will allow the advantages of heliox to be apparent.

RECOMMENDATIONS

NEDU should adopt the proposed limits for WOB for Heliox breathing.

The same statistical technique that has been adopted in making decisions for air diving should be adopted for heliox diving.

THIS PAGE BLANK

REFERENCES

1. D. E. Warkander, *Recommended Amendment to NEDU Technical Manual 01-94: U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus*, NEDU TM 08-17, Navy Experimental Diving Unit, Sep 2008.

2. D. E. Warkander, *Comprehensive Performance Limits for Divers' Underwater Breathing Gear: Consequences of Adopting Diver-focused Limits*, NEDU TR 07-02, Navy Experimental Diving Unit, Jan 2007.

3. Commander, Navy Experimental Diving Unit, *U.S. Navy Unmanned Test Methods and Performance Goals for Underwater Breathing Apparatus*, NEDU Tech Man 01-94, Navy Experimental Diving Unit, June 1994.

4. European Committee for Standardization, *Respiratory Equipment — Open-circuit Umbilical-supplied Compressed Gas Diving Apparatus — Part 1: Demand Apparatus*, European Standard EN 15333, European Committee for Standardization, Jan 2008.

5. European Committee for Standardization, *Respiratory Equipment — Self-contained Re-breathing Diving Apparatus*, European Standard EN 14143, European Committee for Standardization, Sep 2003.

6. J. B. Morrison and S. D. Reimers, ―Design Principles of Underwater Breathing Apparatus," in P. B. Bennett and D. H. Elliot (eds.), *The Physiology and Medicine of Diving*, 3rd ed. (San Pedro, CA: Best Publishing, 1982), pp. 55–98.

7. E. H. Lanphier and E. M. Camporesi, ―Respiration and Exercise," in P. B. Bennett and D. H. Elliot (eds.), *The Physiology and Medicine of Diving*, 3rd ed. (San Pedro, CA: Best Publishing, 1982), pp. 99–156.

8. W. B. Wood, L. H. Leve and D. Workman, *Ventilatory Dynamics under Hyperbaric States*, NEDU TR 01-62, Navy Experimental Diving Unit, May 1962.

9. R. E. Marshall, E. H. Lanphier and A. B. DuBois, ―Resistance to Breathing in Normal Subjects during Simulated Dives," *J. App. Physiol.*, Vol. 9 (1956), pp. 5–10.

10. N. R. Anthonisen, M. E. Bradley, J. Vorosmarti and P. G. Lineweaver, ―Mechanics of Breathing with Helium-Oxygen and Neon-Oxygen Mixtures in Deep Saturation Diving," in C. J. Lambertson (ed.), *Proceedings of the Fourth Symposium on Underwater Physiology* (New York, NY: Academic Press, 1971), pp. 339–345.

11. L. D. H. Wood and A. C. Bryan, ―Effect of Increased Ambient Pressure on Jaw-Volume Curve of the Lung," *J. Appl. Physiol.*, Vol. 27, No. 1 (1969), pp. 4–8.

12. D. A. Williamson and L. Crepeau, *Unmanned and Manned Test and Evaluation of DSI EXO-26 FFM (EXO-26) Using 84/16 Heliox Mixed Gas*, NEDU TR 03-98, Navy Experimental Diving Unit, Oct 1999.

13. M. Briere and D. E. Warkander, *Kirby Morgan Dive Helmet 37 Evaluation (Unmanned)*, NEDU TR 07-05, Navy Experimental Diving Unit, Jan 2007.

14. G. S. Conley, *NOAA Diving Program Underwater Breathing Apparatus: Unmanned Evaluation*, NEDU TR 03-02 (Limited distribution), Navy Experimental Diving Unit, Feb 2003.

15. R. P. Layton, *Next Generation Underwater Breathing Apparatus (NUBA): Unmanned U.S. Navy Certification Evaluation of Carleton Life Support Technologies MK 16 Mod 2 (Revisions 2 through 4)*, NEDU TR 06-11 (Limited distribution), Navy Experimental Diving Unit, Aug 2006.

16. R. P. Layton and D. E. Warkander, *Next generation underwater breathing apparatus (NUBA): Initial Unmanned evaluation of Stealth EOD-M, Mk 16 MOD 2 and Viper E*, NEDU TR 05-17 (Limited distribution), Navy Experimental Diving Unit, Nov 2005.